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Effect of Delta Temperature Minimum Contribution in Obtaining an Operable and Flexible Heat Exchanger Network

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Abstract

This paper presents the control structure decision making for heat exchanger networks (*HENs*) to obtain operable and flexible network. Delta temperature minimum (ΔT_{min}) contribution is considered in this study. Several studies have been done to determine the effect of ΔT_{min}-contribution on the annual cost. Usually, *HENs* designed without consider controllability analysis and control structure decision making. In control structure decision making analysis are done to already designed *HEN*. Design and controllability analysis for HEN are done seperately. Therefore, there are still lacks of studies on how the ΔT_{min}-contribution effects the controllability and control structure desion making. Optimal ΔT_{min} selection is important decision to make in the early stage to avoid inflexible and inoperable heat exchanger networks. The question that needs to be answerd here is how to determine the optimal value of ΔT_{min} that will have better operating conditions that satisfy process design (*HEN*), controllability and as well as economy. In this study, this problem will be formulated as a mathematical programming (optimizattion with constraints) and solved by decomposing it into four hierarchiacal stages: (i) target selection, (ii) *HEN* design analysis, (iii) controllability analysis, and (iv) optimal selection and verification. A case study plant was selected as a case study. Small value of ΔT_{min} was first implemented and will gradually be increased to see the effect on the operability and flexibility of a case study.

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Keywords: Operable and flexible heat exchanger networks; delta temperature minimum; process design; controllability

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1. Introduction

Heat exchanger networks (*HEN*s) are important in chemical processing plant. The purpose of the *HEN* is to heat up cold streams with hot streams that need to be cooled down or vice versa with less cold and hot utilities. It is an arrangement of several heat exchangers to reduce external energy usage in the plant. Optimum design *HEN*s is where the network able to maximize energy recovery with small capital cost design Therefore, it is important to synthesis an optimum *HENs* with the minimum operating and capital costs. Linhoff et al. have started developed Pinch Technology to optimize energy recovery [1].

In designing heat exchanger network, one important parameter that needs to be considered is a delta temperature minimum (ΔT_{min}). ΔT_{min} is used in designing *HEN* in order to balance the trade-off between energy and capital cost. This design target is used to balance energy-capital trade-off. Several researchers have recommended that in order to optimize the *HEN* design, it is need to target and design the optimal cost of *HEN* using ΔT_{min} [2]. Abdullahi has studied ΔT_{min} contribution in which to give lower and accurate total minimum of heat transfer design, it is a common idea to select the value of ΔT_{min} in order to balance the operational and capital cost. ΔT_{min} is a trade-off between operational and capital cost. Sun et al. have investigated on the effect different ΔT_{min} on capital and operating cost for *HEN* with multiple utilities and different types of heat exchangers [3]. Smaller value of ΔT_{min} will minimize the operating cost and maximize the capital cost. On the other hand, larger value of ΔT_{min} will maximize the operating cost and minimize the capital cost [4]. If one selects a smaller value of ΔT_{min}, it indicates that lots of energy can be recovered, however it will require a large heat exchanger area. If one selects a larger value ΔT_{min}, the energy recovery will be less but the heat exchanger area will be smaller [5]. There are still lacks of studies have been conducted on how the ΔT_{min} will effect the controllability of the designed heat exchanger networks (*HEN*s). Optimal ΔT_{min} selection is an important decision to make in the early stage of design to avoid inflexible and inoperable *HEN*s.

The question that needs to be answered here is how to determine the optimal value of ΔT_{min} that will have better operating conditions that satisfy process design (*HENs*), controllability and as well as economy. This paper presents control structure HEN design based on selection of ΔT_{min} value in order to obtain operable and flexible *HENs*. Therefore, here control structure design decision making task is implement in this research. The control structure decision task are adapted from Skogested [6].

2. Methodology

2.1 Problem statement

Multi-objectives function to optimization design and control problem formulated as below based on generic optimization by Russel [7] and been explain in [8].

$$\max(J) = w_{1,1}(P_{1,1}) + w_{2,1}(P_{2,1}) + w_{2,2}(1/P_{2,2}) + w_{3,1}(1/P_{3,1}) + w_{3,2}(1/P_{3,2}) \tag{1}$$

Where there are three design optimization objectives function, $P_{1,1}$ define as energy recovery, $P_{3,1}$ define as operating cost and $P_{3,2}$ define as capital cost. Another two are categorize as control optimization objective function $P_{2,1}$ is define as HEN flexibility and $P_{2,2}$ is define as *HEN* sensitivity. $w_{i,j}$ where i=1-3, and j=1,2 is the weightage of each criteria. Weightage is use to give preference to any criteria than other criteria. The weightage value range can be 0.1 to 1. If all criteria are equally important, the value can be 1.

2.2 Case Study

An example case study is used to implement the method. This example case are from Alwi and Manan [9]

Table 1. A case study is used to implement the method

Stream	Supply temp.	Target temp.	Heat capacity flowrate, FCp(kW/◦C)	Enthalpy, ΔH (kW)
H1	300	160	3	-420
H2	230	120	7	-770
H3	160	60	2	-200
C1	40	230	2	380
C2	100	230	4	520
C3	230	300	3	210

2.3 Stage 1:Target Selection

i. Data from the process flow diagram is extracted. The needed data is stream flowrate (F), heat capacity (C_p), supply temperature (T_s) and target temperature (T_t).
ii. Select ΔT_{min}. For this case study ΔT_{min}= 5^{o}C is first selected. Then continue to next step which is to develop Problem Table Algorithm (*PTA*) diagram.
iii. Develop Problem Table Algorithm (*PTA*) based on Klemes *et al.*, 2010.
iv. Construct Composite Curve (*CC*) and Grid Diagram (*GD*). From the grid diagram, duty for each heat exchanger can be identified and temperatures (in and out) can be calculated. All the information from Stage 1 is then transferred to Stage 2.

2.4 Stage 2 Heat Exchanger Network Analysis

i. From the information obtained in Stage 1, *HENs* will be constructed. Temperatures in and out that were calculated in stage 1 will be inserted to the process simulator such as Aspen *HYSYS*. In this step, only feasible *HEN* candidates will proceed to the next stage. If the designed *HEN* is not feasible based on the selected value of ΔT_{min}, for example has problem with the warning such as "Ft correction factor is low", then, a new value of ΔT_{min} is selected in Stage 1. For *HEN* designed at ΔT_{min} = 5 ^{o}C, there are six heat exchangers. However, after transferred all the information into Aspen *HYSYS*, it showed a warning of "Ft correction factor is low". Therefore, *HEN* designed at ΔT_{min} = 5 ^{o}C is not feasible. Then, a new value of ΔT_{min} is selected in step 1.2
ii. For this case study, there are 8 different values of ΔT_{min} are being tested, ΔT_{min}= 5^{o}C, 10^{o}C, 15^{o}C, 20^{o}C, 25^{o}C, 30^{o}C, 35^{o}C, 40^{o}C

2.5 Stage 3: Controllability Analysis

In controllability analysis, selection of manipulated variable and degree of freedom analysis are done adapted from Skogested[6]. This study considers controllability analysis in steady state mode. Optimization degree of freedom, N_{opt} is degrees of freedom that effect controllability objective function. Manipulated variables, N_m are identified. Manipulated variables usually are variables that can be adjusted using mechanical device such as valve. N_0 is the number variables that not effect to the controllability objective function. N_0 is manipulated input and controlled output variables that have no effect to controllability objective function. See Eq. 2 After the variables are obtained, next is to proceed to these analysis.

$$N_{opt} = N_m - N_0 \quad (2)$$

Manipulated variables that effect to the objective function:
HEN at ΔT_{min}= 35ºC are feed flowrate for H_1, H_2, C_1, C_2
HEN at ΔT_{min}= 40ºC are feed flowrate for H_1, H_2, C_1, C_2
Control variables that effect to the objective function:
HEN at ΔT_{min}= 35ºC are temperature for $H_{1output}$, $H_{2output}$, $C_{1output}$, $C_{2output}$
HEN at ΔT_{min}= 40ºC are temperature for $H_{1output}$, $H_{2output}$, $C_{2output}$

In this case study it is consider as open-loop control strategy with steady state optimization. Self-optimizing strategy is used in this case study.

i. Flexibility analysis: *HEN* candidates that passed Stage 2 will be further analyzed in terms of flexibility. The idea is to analyze how flexible the designed *HEN* when changes manipulated variable. In this study, is the feed flowrate. The feed flowrate for each stream of the *HENs* candidates will be increase. Heat exchangers condition in the network will be monitored. If the heat exchanger is not showing any warning, feed flowrate will be increased until the warning from process simulator is shown. The highest tolerable feed flowrate is noted and percentage flowrate increments will be calculated. Average percentage tolerable manipulated variables for a *HEN* will be as calculated.
ii. Sensitivity analysis: In this analysis, *HEN* candidates will also be analyzed in terms of sensitivity with respect to changes input variable (disturbances). In this case feed temperatures are consider as disturbance. In this step, feed temperature for each stream will be changed about ±1% or less from the initial temperature and the status heat exchangers in the network in the Aspen *HYSYS* environment will be monitored.
iii. Controller structure analysis: Same manipulated variable in flexibility analysis is used in this analysis. Here, controller structure for feasible *HEN* is selected by calculating derivative value of controlled variable with respect to manipulated variable. The highest derivative value of controlled variables with respect of disturbance will be the best pairing. Finally, process gain to determine the best pairing control structure for *HEN* design.

2.6 Stage 4: Optimal Selection and Verifications

HEN candidates that passed through Stage 3 will be analysed in terms of capital and operating costs in this step. The *HEN* candidate with the lowest capital and operating costs will be selected as the best/optimal design for *HEN*. The value of ΔT_{min} used to design the optimal *HEN* is the optimal one that satisfies process design, controllability, and economy criteria. To verify control aspect, relative gain array (*RGA*) is done to determine the interaction of control structure pairing with others.

3. Results and Discussions

Eight candidates have been analysed using this method. After stage 2, only 2 candidates pass *HEN* analysis (feasibility test) which are ΔT_{min}= 35ºC, 40ºC. These candidates are then being analysis the degree of freedom of each *HEN* design. Table 2 shows result summary of the Stage1 to Stage 4. Fig. 1 shows control structure of each *HEN* candidates.

Table 2. *HEN* design results at different *ΔTmin*.

ΔT_{min} (ºC)	5	10	15	20	25	30	35	40
Energy Recovery (kW)	1080	1050	1020	990	960	930	900	870
Utility energy (kW)	340	400	460	520	580	640	760	760
Feasible	No	No	No	No	No	No	Yes	Yes
Flexibility (%)	-	-	-	-	-	-	51.55	53.36
Sensitivity (%)	-	-	-	-	-	-	11.14	10.64

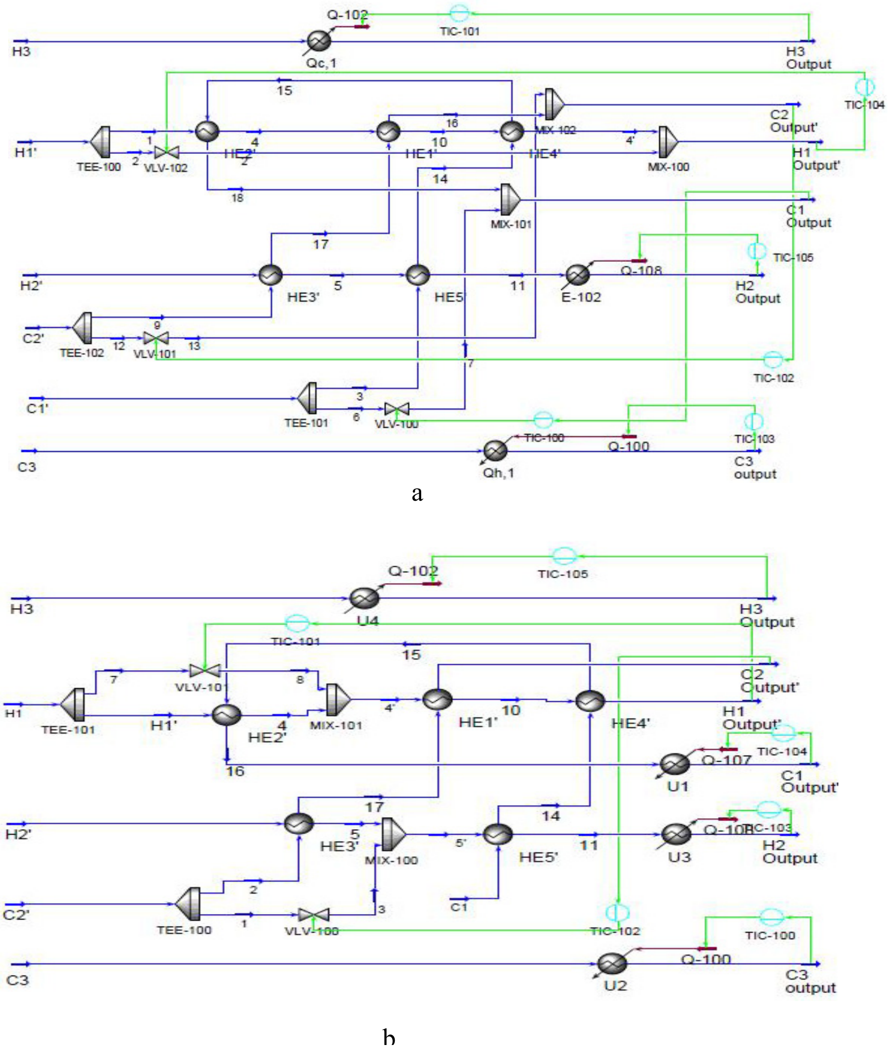

Fig. 1. Control structured Design *HEN* at different ΔT_{min} (a) ΔT_{min}= 35ºC (b) ΔT_{min}= 40ºC

4. Conclusions

This paper presents on the control structure decision making to obtain operable and heat exchanger network. Delta temperature minimum (ΔT_{min}) contribution in order to obtain the best operable and flexible *HENs*. Optimal ΔT_{min} selection is important decision to make in the early stage to avoid inflexible and inoperable heat exchanger networks. The selection of the optimal ΔT_{min} can be obtained with the help the developed methodology for designing flexible and operable *HEN*s. Accordingly, the problem is formulated as a mathematical programming (optimizattion with constraints) and solved by decomposing it into four hierarchiacal stages: (i) target selection, (ii) *HEN* design analysis, (iii) controllability analysis, and (iv) optimal selection and verification. *HEN* design is considered optimally operated when the target temperatures are satisfied at steady state, the utility cost is minimized and the dynamic behavior and control aspects are best satisfied. Two different *HEN* design with control pairing are obtain in this paper based on this methodology.

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